

BORE II – A Code to Compute Dynamic Wellbore Electrical Conductivity Logs with Multiple Inflow/Outflow Points Including the Effects of Horizontal Flow across the Well

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Abstract

Dynamic wellbore electrical conductivity logs provide a valuable means to determine the flow characteristics of fractures intersecting a wellbore, in order to study the hydrologic behavior of fractured rocks. To expedite the analysis of log data, a computer program called BORE II has been developed that considers multiple inflow or outflow points along the wellbore, including the case of horizontal flow across the wellbore. BORE II calculates the evolution of fluid electrical conductivity (FEC) profiles in a wellbore or wellbore section, which may be pumped at a low rate, and compares model results to log data in a variety of ways. FEC variations may arise from inflow under natural-state conditions or due to tracer injected in a neighboring well (interference tests). BORE II has an interactive, graphical user interface and runs on a personal computer under the Windows operating system. BORE II is a modification and extension of an older code called BORE, which considered inflow points only and did not provide an interactive comparison to field data. In this report, we describe BORE II capabilities, provide a detailed user's guide, and show a series of example applications.

1. Introduction

The variation of formation permeability surrounding a wellbore is useful information not only for identifying hydraulically conducting fractures or other high-conductivity features intercepted by the well, but also for quantifying the heterogeneity of the medium. These are essential data in the evaluation of in-situ flow and transport characteristics at a given site.

Methods to evaluate permeability values along the depth of a well include the packer method, in which constant pressure, constant flow, or pulse tests are conducted in packed-off intervals in a wellbore, and various downhole flow meters. The packer method has the disadvantage that it is very time consuming and costly, and the vertical resolution is limited by the interval between the two packers that can be set in the well. Flow meter methods such as spinners and heat pulse flow meters generally allow better vertical resolution than the packer method, but they are not as accurate in determining permeability, because they mostly measure the wellbore fluid velocity, which is very sensitive to variations in the wellbore radius.

In 1990, Tsang et al. (1990) proposed a method using logs of fluid electric conductivity (FEC) at successive times under constant-pumping conditions to obtain inflow from the formation into the well as a function of depth in the well. In this method, the wellbore is first filled by de-ionized water or water of a constant salinity (i.e., ion concentration) distinct from that of the formation water. This is usually done by passing the de-ionized water down a tube to the bottom of the wellbore at a given rate while simultaneously pumping at the top of the well at the same rate. After this is done, the well is pumped at a constant flow rate, which can be adjusted to optimize wellbore flow conditions. An electric resistivity probe is lowered into the wellbore to scan FEC as a function of depth along the wellbore. This is what is called fluid conductivity logging. A series of five or six such logs are obtained at time intervals over a one- or two-day period. At the depth levels where water enters the wellbore, the conductivity log displays peaks, which grow with time and become skewed in the direction of water flow. By analyzing these logs, it is possible to obtain the permeability and salinity of each hydrologic layer transmitting water. The method has been very successful, being much more accurate than flow meters and much more efficient (much cheaper) than packer tests (Tsang et al. 1990), particularly in low permeability formations. A typical 1000-m section in a deep hole can be tested in two or three days at a spatial resolution of ~ 0.10 m all along the length of the wellbore

section. The method is now being widely used in Europe and the U.S. (Marschall and Vomvoris, 1995; Pedler et al., 1992; Bauer and LoCoco, 1996), both under natural-state flow conditions and while tracer is injected in a neighboring well (i.e., interference tests).

Along with the method, a code was developed called BORE (Hale and Tsang, 1988), which performed the forward calculation to produce wellbore FEC profiles given different inflow positions, rates, and concentrations. The code has been well used over the last decade. However, it appears now that there is a need to revise the code to make it more suitable for current computer environments and to add new capabilities. Thus, the code has been updated to run under current operating systems, provide interactive modification of model parameters, and produce graphical comparisons between model and field data. More importantly, the revised code allows the possible inclusion of both flows into and out of the well at various depths, a feature that has been observed in real field conditions when different layers penetrated by the well have different hydraulic heads. Furthermore, the new code allows the calculation of the case with equal inflow and outflow at the same depth level, which is effectively the special case of horizontal flow across the wellbore. Drost et al. (1968) proposed a measurement of solute dilution in the wellbore to evaluate ambient horizontal flow velocity in the formation and it has become a well-accepted method. The new code provides the opportunity to analyze such cases and to identify the depth interval of horizontal flow to within ~ 0.1 m as well as to estimate the flow rate. Moreover, one can analyze the combination of horizontal flow across the wellbore and vertical diffusion or dispersion along the length of the wellbore, which is not possible with Drost's solution.

The report is organized as follows. In Section 2, the basic capabilities of the revised code, called BORE II, are described, and the key parameters associated with BORE II are defined. Details of the mathematical background and numerical approach are described in Appendix 1, which is adapted from Hale and Tsang (1988). A user's guide is presented in Section 3, which includes a description of BORE II's interactive user interface, required input items, and options available when running BORE II. Four example applications are given in Section 4 to conclude the report.

We are still open to further improvements of BORE II; any suggestions and comments are invited and should be addressed to the authors.

2. BORE II Capabilities

BORE II calculates FEC as a function of space and time in a wellbore containing multiple feed points given the pumping rate of the well, the inflow or outflow rate of each feed point, its location and starting time, and, for inflow points, its ion concentration. A simple polynomial correlation between ion concentration, C , and FEC is assumed. Ion transport occurs by advection and diffusion along the wellbore, with instantaneous mixing of feed-point fluid throughout the wellbore cross-section. These assumptions allow use of a one-dimensional model. BORE II divides the wellbore section under study into equal height cells and solves the advection/diffusion equation using the finite difference method. Further details of the mathematical and numerical approach are given in Appendix 1.

Inflow and Outflow Feed Points

The original BORE code (Hale and Tsang, 1988) considered inflow points only, so flow through the wellbore was upward at all depths. BORE II allows both inflow and outflow points, so flow in the wellbore can be upward, downward, or horizontal at different depths and flow at either end of the wellbore section being studied can be into or out of the wellbore section or be zero. By convention, upward flow in the wellbore is positive and flow into the wellbore is positive.

Steady and Varying Fluid Flow

The original BORE code considered steady fluid flow, so feed points had constant flow rates. They also had constant concentrations, but delayed starting times for feed-point concentration to enter the wellbore were allowed. BORE II permits both steady and varying fluid flow. For the steady-flow case, the user specifies flow rate, concentration, and concentration start time for each feed point, but for outflow points (those with negative flow rates) the concentration and concentration start time are not used. Variable flow rate or concentration can be specified for feed points by interpolating from a table of time, flow rate, and concentration. If a table includes both positive and negative flow rates (i.e., a feed point alternates between inflow and outflow), the concentration for the positive flow rate is used when interpolating between positive and negative flow rates.

Concentration Boundary Conditions

If the flow at the top of the wellbore section under study is into the wellbore, the initial concentration for the uppermost cell in the wellbore is used as the inflow concentration. Analogously, if flow at the bottom of the wellbore section is a flow up from greater depths, the initial concentration for the lowermost cell in the wellbore is used as the inflow concentration. Furthermore, for inflow points with a concentration start time greater than zero, the initial concentration of the wellbore is used as the inflow concentration for times less than concentration start time.

Horizontal Flow

The special case of horizontal flow through the wellbore, as described by Drost et al. (1968), can also be considered, by locating an inflow point and an outflow point with equal magnitude flow rates at the same depth. The flow rates may be specified as either (1) the Darcy velocity through the aquifer or (2) the volumetric flow rate into/out of the wellbore. BORE II multiplies Darcy velocity by the cross-sectional area of the feed point (wellbore diameter times cell height) and Drost's α_h convergence factor to convert it to a volumetric flow rate. The value of α_h can range from 1 (no convergence) to 4 (maximum possible convergence, which occurs for the case of a thick, highly-permeable well screen). Drost suggested that for a uniform aquifer with no well screen, $\alpha_h = 2$, and that for typical applications, a good choice for α_h is 2.5. Horizontal flow feed points may have time-varying flow rates, but for Darcy-velocity calculations to make sense, the inflow and outflow rates must be equal and opposite at any time. Thus, if a feed point location changes from a horizontal flow point to a non-horizontal flow point with time, volumetric flow rates must be specified rather than Darcy velocities.

BORE II Parameters

The key parameters associated with BORE II are defined below.

Parameter	I/O units*	Description
C	g/L	Ion concentration in the wellbore; converted to FEC using $FEC = \gamma + \beta C + \alpha C^2$, where α , β , and γ are user-specified constants (default values are provided in the code, see Section 3)
C_i	g/L	Ion concentration of i th feed point
C_0	g/L	Initial ion concentration in wellbore
D_0	m^2/s	Diffusion coefficient (may include dispersive effects as well molecular diffusion)
d_w	cm	Wellbore diameter (assumed constant)
FEC	$\mu S/cm$	Fluid electrical conductivity
q	L/min	Fluid flow rate in wellbore (upward flow is positive)
q_i	L/min	Fluid flow rate of i th feed point; positive for inflow and negative for outflow
q_w	L/min	Fluid flow rate in wellbore at x_{\max} , specified by the user
q_0	L/min	Fluid flow rate in wellbore at x_{\min} (or any depth of interest), calculated internally
T or TEMP	$^{\circ}C$	Temperature (assumed constant)
t	hr	Time
t_{\max}	hr	Maximum simulation time
t_{0i}	hr	Concentration start time of i th feed point
v_d	m/day	Darcy velocity through aquifer for horizontal flow ($q_i = v_d \alpha_h \Delta x d_w$)
x	m	Depth (positive, increases down the wellbore)
x_{\min}, x_{\max}	m	Top and bottom, respectively, of wellbore interval being studied
Δx	m	Cell height for wellbore discretization
α_h	—	Drost et al. (1968) convergence factor for horizontal flow

*I/O units are chosen for convenience; all quantities are converted to SI units before BORE II calculations.

3. BORE II User's Guide

Operating System

BORE II may be run under Windows 95, 98, or 2000 by double-clicking the executable icon (BOREII.EXE) in Windows Explorer, by double-clicking on a desktop shortcut key to BOREII.EXE, or by typing BOREII in the Run command in the Start Menu or in a DOS-prompt window. BORE II will not run in stand-alone DOS or in the DOS-mode of Windows. BORE II was compiled using Microsoft Fortran PowerStation™ Version 4.0, but this software is not necessary to run the program.

BORE II Graphical Output

The primary user interface with BORE II is interactive, with the user responding to on-screen prompts to modify model parameters and choose options (described below) for the real-time graphical display of model results and data. The basic BORE II output screen consists of three windows.

- The borehole profile window shows FEC profiles as a function of depth and time. Simulation time t is shown in the upper left corner. Fluid flow rate at a user-specified depth in the wellbore, q_0 , is shown in the middle of the top line (the depth at which q_0 is calculated is set by option P). The depth of a C - t plot is also shown.
- The inflow parameters window shows the feed-point characteristics for the model that can be modified with option M (location, flow rate, and concentration). Often there are more feed points than can be displayed at once on the screen. BORE II starts out showing the first few (deepest) feed points, then shows the feed points in the neighborhood of any point that is being modified.
- The dialog window allows the user to select options (described below) when running BORE II.

On computers with small screens, it may be desirable to run BORE II in full-screen mode, so that the entire BORE II screen can be seen at once without scrolling. Full-screen mode is entered by pressing Alt-VF (or on some computers by pressing Alt-Enter). Pressing Esc (or

Alt-Enter) terminates full-screen mode. There are three potential problems associated with the use of full-screen mode.

- (1) The status line describing what BORE II is doing (e.g., running, waiting for input) is not visible.
- (2) Drawing an x - t plot (options X, S, D, F, and I), which creates a new window, may be very slow and the graphics quality poor.
- (3) On some computers, text is difficult to read after closing the x - t plot window.

To address the latter two problems, one may terminate full-screen mode before using options X, S, D, F, and I. The new window will be small, but after drawing is complete it may be expanded by pressing Alt-VF to enter full-screen mode. Full-screen mode should be terminated before the new window is closed to avoid the final problem.

To print an image of the screen, press Alt-PrintScreen to copy the screen image into the clipboard. Then open a program such as Microsoft Paint and paste in the image. It can be manipulated, saved in a variety of graphics formats, or printed from Paint. The image can also be pasted directly into another Windows application such as MS Word.

Input/Output File Overview

Running BORE II requires one or two external files: a file with an initial set of model input parameters (mandatory, known as the input file) and a file with observed data (optional, known as the data file). These files are plain ASCII text, and must reside in the same folder as the BORE II executable. The input file contains model parameters such as the depth interval being studied, feed point characteristics, problem simulation time, and C -to-FEC conversion factors. The data file contains observed values of FEC and temperature, and optionally contains other fluid properties such as pH. Detailed instructions for preparing an input file and a data file are given below.

BORE II always creates a temporary file, called BOREII.TMP (see options C and R), and optionally creates a new input file (see option V), which is useful if model parameters have been changed during the BORE II run.

Line-by-line Instructions for Input File

After starting BORE II, the user is prompted to choose the input file from the list of files residing in the folder where the BORE II executable is. Input file names with more than 8 characters before a period or blanks will appear in the list of files in an abbreviated form. File names can be at most 20 characters long.

A sample input file is provided that can be modified as needed using a text editor such as Notepad or a word processor such as MS Word. If a word processor is used to create or modify an input file, be sure that the file is saved as plain ASCII text.

The input file is designed to be self-documenting, with header lines preceding data lines. These header lines must be present, but BORE II does not use the text on them. Data entries are read in free format, with individual entries on a given line separated by blanks, tabs, or commas. This means that entries cannot be left blank, even if they are not being used (e.g., concentration for an outflow point). Unused entries may be set to zero or any convenient value. Comments may be added on data lines, after the requisite number of entries. In the sample input file, comments begin with an exclamation point.

Item	Computer Variables	Unit	Description
1.	TITLE	–	A description of the problem, 80 characters maximum
<i>2 header for wellbore geometry</i>			
2.	RXMIN	m	Top of study area, x_{\min}
	RXMAX	m	Bottom of study area, x_{\max}
	RDIAM	cm	Wellbore diameter, d_w
<i>3 header for flow parameters</i>			
3.	RQW	L/min	Flow into (positive) or out of (negative) the bottom of the study area, q_w
	HALPHA	–	Factor to account for convergence of horizontal flow lines toward the wellbore, α_h (Drost et al., 1968) Range: 1.0 – 4.0; default value: 2.5 Only used for horizontal flow

<i>4 header for feed points</i>			
4.	IINFN	–	Number of feed points (maximum 180)
	IQFLAG	–	Variable flow-rate flag – a 3 digit integer used to identify feed points with variable flow (suggested value 999)
<i>5 header for constant-flow-rate feed points</i>			
5. Repeat IINFN times	RINFX	m	Location of feed point, x_i^* For horizontal flow put two feed points at the same location, with equal magnitude, opposite sign flow rates
	RINFQ	L/min (m/day if IINFV=1)	Constant inflow rate (positive) or outflow rate (negative) of feed point, q_i For a variable flow rate, set RINFQ = IIIJJ, where III = IQFLAG, and JJ is a two digit integer giving the number of times in the variable-flow-rate table, which follows in 5a For horizontal flow, v_d replaces q_i if IINFV = 1
	RINFC	g/L	Constant feed point concentration, C_i - only used for inflow points For a variable concentration, set RINFQ = IIIJJ, where III = IQFLAG, and JJ is a two digit integer giving the number of times in the variable-flow-rate table, which follows in 5a
	RINFT	hr	Start time for constant feed point concentration, t_{0i} - only used for inflow points Feed point concentration is C_0 of cell containing feed point for $t < t_{0i}$
	IINFV	–	Horizontal flow Darcy-velocity flag (must be zero for non-horizontal flow case): = 0: RINFQ is flow rate q_i into/out of the wellbore in L/min = 1: RINFQ is +/-Darcy velocity v_d through the aquifer in m/day

<i>5a header for variable-flow-rate table (only when RINFQ = IQFLAGJJ)</i>			
5a. Repeat JJ times when RINFQ = IQFLAGJJ	RINFQT	hr	Time t_j (set $t_1 = 0$, set $t_{JJ} > t_{\max}$)
	RINFQQ	L/min (m/day if IINFV=1)	Volumetric flow rate q_j at time t_j For horizontal flow, v_d replaces q_j if IINFV = 1
	RINFCC	g/L	Concentration C_j at t_j
<i>6 header for misc. parameters</i>			
6.	TMAX	hr	Maximum simulation time, t_{\max}
	DPYMAX	$\mu\text{S/cm}$	Maximum FEC for plots
	RK	m^2/s	Diffusion coefficient, D_0
<i>7 header for C-to-FEC conversion</i>			
7.	RGAMMA	$\mu\text{S/cm}$	Conversion from C in g/L to FEC in $\mu\text{S/cm}$: $\text{FEC} = \gamma + \beta C + \alpha C^2$
	RBETA	$[\mu\text{S/cm}]/[\text{g/L}]$	
	RALPHA	$[\mu\text{S/cm}]/[\text{g/L}]^2$	Default values (for 20°C): $\gamma = 0$, $\beta = 1870$, $\alpha = -40$ Set $\gamma = 0$, $\beta = 1$, $\alpha \approx 1.e-8$ for $\text{FEC} \approx C$
<i>8 header for initial conditions</i>			
8.	IC0FLAG	–	Initial concentration flag: = 0: $C_0 = 0$, no further input for item 8 < 0: read uniform non-zero C_0 in 8a > 0: read IC0FLAG ($x, C_0(x)$) pairs in 8b to describe variable initial concentration
<i>8a header for uniform initial conditions (only when IC0FLAG < 0)</i>			
8a. when IC0FLAG<0	RC0	g/L	Uniform non-zero C_0
<i>8b header for non-uniform initial conditions (only when IC0FLAG > 0)</i>			
8b. repeat IC0FLAG times when IC0FLAG>0	RX	m	x value*
	RC0	g/L	$C_0(x)$
<i>9 header for data file name</i>			
9.	CFDATA	–	Name of data file, 20 characters maximum; 'NONE' if there is no data file

*see Appendix 1, Section A1.5, for additional information on locating feed points and specifying non-uniform initial conditions

Sample Input File

An input file illustrating many of these options is shown below. Text or numbers following an exclamation point (!) are comments, and are not used by BORE II.

```

TITLE: Sample Input File with flow from below, horizontal flow, variable flow
XMIN (m)      XMAX (m)      DIAM (cm)
.0000         60.00         7.600
QW (L/min)    HALPHA      !QW=flow from below; HALPHA=hor. flow constriction
0.50         0.           !default value of HALPHA will be used
#FEED_PTS     VARIABLE_FLOWRATE_IDENTIFIER
4            999
DEPTH (m)     Q (L/min)     C (g/L)      T0 (hr)      Q/V_FLAG
25.          +1.           6.0          .0000       1 !1st 2 feed pts-hor. flow
25.          -1.           6.0          .0000       1 !C & T0 not used (outflow)
30.          99905.        6.0          .0000       0 !C & T0 not used (table)
      T (hr)      Q (L/min)     C (g/L)      !#entries is two digits after 999
      .0000      .0000         6.           !first time in table is zero
      .3000      .2800E-01      5.
      .5000      .3200         4.
      1.000      .4600         3.
      1.500      .4600         2.           !last time in table is > tmax
35.          .5            4.0          .2000       0 !final feed pt
TMAX (hr)     FECMAX      DIFFUSION_COEF. (m2/s)
1.000         5000.       .7500E-09
RGAMMA        RBETA      RALPHA      !FEC = RGAMMA + C*RBETA + C*C*RALPHA
0.            0.          0.           !default values will be used
IC0FLAG       !If 0, C0=0; If <0, read one C0; If >0, read IC0FLAG (X,C0) pairs
1
X (m)         C0 (g/L)      !#entries is IC0FLAG
60.           2.           !Concentration associated with Qw
DATA_FILE     !'NONE' if there is no data file
NONE

```

The first two feed points represent constant horizontal flow, and since the Q/V flag (IINFV) is one, flow rate is given as Darcy velocity through the aquifer in m/day. The third feed point has variable flow rate and concentration, with a five-entry table specifying the variation with time. The fourth feed point is an inflow point with constant flow rate and concentration and a non-zero concentration start time.

Note that the flow from below, q_w , is positive (into the wellbore section), so the corresponding concentration is specified as the initial condition of the lowermost cell in the wellbore (at $x = x_{\min}$) by using IC0FLAG = 1. If IC0FLAG = 0, the concentration associated with q_w would be zero, and if IC0FLAG = -1, the concentration associated with q_w would be the uniform non-zero initial concentration in the wellbore.

When BORE II writes an input file (option V), it changes several things to the file form shown above. Comments found in the original input file are not reproduced, but two comments are added. First, the cell height and the equation used to calculate it are shown on the line with x_{\min} , x_{\max} , and d_w . Second, if feed points represent horizontal flow, then the flag IINVF is set to 0, flow rate is given in L/min, and the corresponding Darcy velocity through the aquifer in m/day is added as a comment. Finally, if IC0FLAG > 0, BORE II sets IC0FLAG to the number of wellbore cells, and explicitly shows every $(x, C_0(x))$ pair. This option is useful for identifying the x values of various cells, which may expedite assignment of feed point locations or initial conditions. Part of the input file created by BORE II for the above sample is shown below.

```

TITLE: Sample Input File with flow from below, horizontal flow, variable flow
XMIN(m)      XMAX(m)      DIAM(cm)      !DX(m) = MAX(|XMIN - XMAX|/180, DIAM/100)
.0000        60.00        7.600      ! .3333
QW(L/min)    HALPHA      !QW=flow from below; HALPHA=hor. flow constriction
.5000        2.500
#FEED_PTS    VARIABLE_FLOWRATE_IDENTIFIER
4            999
DEPTH(m)     Q(L/min)     C(g/L)      T0(hr)      Q/V_FLAG    !Vd(m/day)
35.00        .5000        4.000      .2000        0
30.00        99905.       6.000      .0000        0
      T(hr)      Q(L/min)     C(g/L)      !#entries is two digits after 999
      .0000      .0000        6.000
      .3000      .2800E-01    5.000
      .5000      .3200        4.000
      1.000      .4600        3.000
      1.500      .4600        2.000
25.00        .4398E-01    6.000      .0000        0      ! 1.000
25.00        -.4398E-01    6.000      .0000        0      !-1.000
TMAX(hr)     FECMAX      DIFFUSION_COEF.(m2/s)
1.000        5000.       .7500E-09
RGAMMA       RBETA      RALPHA      !FEC = RGAMMA + C*RBETA + C*C*RALPHA
.0000        1870.       -40.00
IC0FLAG      !If 0, C0=0; If <0, read one C0; If >0, read IC0FLAG (X,C0) pairs
179
X(m)         C0(g/L)      !#entries is IC0FLAG
59.83        2.000
59.50        .0000
59.17        .0000
58.83        .0000
...(169 entries with C0=0 not shown)...
2.167        .0000
1.833        .0000
1.500        .0000
1.167        .0000
.8333        .0000
.5000        .0000
DATA_FILE    !'NONE' if there is no data file
NONE

```

Line by Line Instructions for Data File

The data file is read in the fixed format shown below. If data are available in a different format, an auxiliary program should be used to convert it to this form (a simple preprocessor called PREBORE, described in Appendix 2, converts the data file format used by BORE to the new format shown below). Note that because a fixed format is used, blank entries are allowed; they are interpreted as zero.

Lines 1-8 are header lines, not used by BORE II.

Each line of the remainder of the file contains:

Variable	x	FEC	TEMP	DAT3	DAT4	DAT5	HR	MIN	SEC
Units	m	$\mu\text{S/cm}$	$^{\circ}\text{C}$				–	–	–
Format	F10.3	F10.3	F10.3	E10.3	E10.3	E10.3	I3	I2	I2
Columns	1-10	11-20	21-30	31-40	41-50	51-60	62-64	66-67	69-70

The entries DAT3, DAT4, and DAT5 represent optional data types that may be collected with certain logging tools, such as pH and dissolved oxygen (see options A and Y for ways to display this data). Note that there is one blank column before each of the HR, MIN, and SEC entries, to make the data file more readable. The first time entry corresponds to $t = 0$ for the model.

BORE II Options

The following options are available on the BORE II main menu. Either uppercase or lowercase letters may be used, and should be followed by pressing ENTER.

C – (C)-x plot – Displays FEC versus depth for data and/or model continuously in time (an animation); stores [x (m), t (sec), data FEC ($\mu\text{S/cm}$), model FEC ($\mu\text{S/cm}$)] in file BOREII.TMP for later use by option R or post-processing.

T – c-(T) plot – Displays FEC versus time for data and model for a chosen depth.

R – d/m cu(R)ve – Displays FEC versus depth plots for data and model at a series of times (snapshots of the option C display); uses results of most recent option C, read from BOREII.TMP. Does not work if there is no data file or if there are only data at one depth in data file.

N – i(N)flow-c – Displays inflow FEC for a chosen feed point as a function of time.

A – p(A)ram display – Displays all data profiles (FEC, TEMP, DAT3, DAT4, DAT5) simultaneously, using user-specified plot limits (selections 3-6). For selection 1, all points are connected on one continuous curve; for selection 2, points that are beyond depth or time limits start new curve segments.

X – (X)-t plot – Displays a color-coded plot of model FEC versus depth and time in a new window, then repeats the plot in the borehole profile window.

S – tool (S)tudy x-t plot – Same as X, but limits display to what would be obtained with a tool whose parameters (number of probes, gap between probes, and tool velocity) are specified by the user.

D – (D)ata x-t – Displays a color-coded plot of data traces versus depth and time in a new window, then repeats the plot in the borehole profile window (data type specified by option Y, default is FEC).

F – (F)ill data x-t – Same as D, except that data traces are interpolated to fill the $x-t$ plane.

I – d/m d(I)ff x-t – Displays a color-coded plot of the difference between model and data FEC versus depth and time in a new window, then repeats the plot in the borehole profile window. User selects whether to show data traces (mode 1) or filled data (mode 2).

M – (M)odify inp– Opens interactive session for modifying location, flow rate, and concentration of feed points, or adding new feed points. User is prompted to enter feed point number and given the chance to modify or maintain current parameters. To add a new feed point, specify a feed point number greater than that for any existing feed point. If horizontal flow is implemented using option M, flow rate must be specified as volumetric flow rate through the wellbore in L/min.

P – (P)lot adjust – Sets new values of parameter minimum and maximum; t_{\max} ; difference range for option I; and depth for which wellbore flow rate q_0 is displayed in borehole profile window (default depth is x_{\min}).

G – (G)rid – Sets grid spacing for new window showing $x-t$ plots.

Y – data t(Y)pe – Chooses data type (FEC, TEMP, DAT3, DAT4, DAT5) to display in options C, T, D, and F. Model results always show FEC, so option C and T plots, which show both model and data, must be read carefully. Note that options R and I are not affected by the choice of data type, but always compare model and data FEC.

Z – print – Displays instructions for printing a screen image.

V – sa(V)e – Creates a new input file with current model parameters. User is prompted for new file name.

Q – (Q)uit – Terminates BORE II program.

4. Example Applications

Five example applications are presented to illustrate the capabilities of BORE II. Although BORE II simulates the forward problem (it produces wellbore FEC profiles given different inflow positions, rates, and concentrations), it is most commonly used in an inverse mode, in which inflow positions, rates and concentrations are varied by trial and error until the model matches observed values of wellbore FEC profiles. Initial guesses for the trial and error process may be obtained using direct integral methods (Tsang and Hale, 1989; Tsang et al., 1990) or other means (see example 2 below). Example applications 3, 4, and 5 demonstrate such comparisons to real data provided to us as typical field data sets by G. Bauer (private communication, 2000). The results of these example applications do not necessarily provide physically realistic flow rates and inflow concentrations, because they employ the artificial equality $FEC = C$. Furthermore, rough matches to real data, as are obtained here, can often be obtained equally well with a variety of different parameters (i.e., the solution of the inverse problem is non-unique). The input files for the example applications are shown in Appendix 3.

	Problem	Data File	Input File	Features
1	Up flow	up_num.dbt (numerically simulated)	up_num.inp	Advection and dilution, diffusion/dispersion minor
2	Horizontal flow	hor_an.dbt (analytical solution)	hor_an.inp	Dilution only, no advection or diffusion/dispersion One pair inflow/outflow points
3	Horizontal flow	hor_real.dbt (real data)	hor_real.inp	Dilution and diffusion/dispersion Multiple pairs inflow/outflow points Initial time added to data
4	Down flow	down_c.dbt (real data)	down_c.inp	Advection, dilution, and diffusion/dispersion Variable inflow concentration
5	Combination flow	comb_ic.dbt (real data)	comb_ic.inp	Advection, dilution, and diffusion/dispersion Non-uniform initial conditions

1. Up Flow – Numerically Simulated Data

Perhaps the most common application of BORE II is to the case of up flow - when one pumps from the top of the wellbore section, and fluid enters the wellbore at one or more feed points. Figure 1 shows C versus x for several times for a typical up flow case (obtained with BORE II option R). Each feed point has the same inflow rate and the same concentration, and there is also up flow from below. At early times, the feed points show up as individual FEC peaks, but as time passes, the deeper peaks merge with those above them, creating a step-like structure. The data set for this example is not real, but the results of a numerical simulation using the flow and transport simulator TOUGH2 (Pruess, 1987; 1991; 1995; 1998). TOUGH2 has been verified and validated against analytical solutions, other numerical models, and laboratory and field data. The TOUGH2 simulation uses a one-dimensional model with the same cell spacing as BORE II and constant mass sources located at the BORE II feed points. Thus, BORE II and TOUGH2 are solving the same problems, and comparing the results for wellbore FEC profiles verifies that the BORE II calculations are done correctly.

2. Horizontal Flow – Analytical Solution and Numerically Simulated Data

For horizontal flow in the absence of diffusion/dispersion along the wellbore, an analytical solution for the concentration observed in the wellbore as a function of time, $C(t)$, is given by (Drost et al., 1968):

$$C(t) = C_i - [C_i - C(0)] \exp\left(\frac{-2tv_d\alpha_h}{\pi r_w}\right), \quad (1)$$

where C_i is the formation (inflow) concentration, t is time (s), v_d is the Darcy velocity through the aquifer (m/s), α_h is the aquifer-to-wellbore convergence factor, and r_w is the wellbore radius (m). Figure 2 shows the analytical solution and the BORE II results for this problem, obtained using option T. The agreement is excellent. Note that for small values of v_d , if $C(0) = 0$, the analytical solution becomes approximately

$$C(t) = C_i \left[1 - \exp\left(\frac{-2tv_d\alpha_h}{\pi r_w}\right) \right] \approx C_i \left[1 - \left(1 - \frac{2tv_d\alpha_h}{\pi r_w} \right) \right] = \frac{C_i 2tv_d\alpha_h}{\pi r_w}. \quad (2)$$

Thus, any combination of C_i and v_d whose product is a constant gives the same value of C . This condition corresponds to the early-time straight-line portion of Figure 2. The analytical solution may be implemented in a spreadsheet to expedite the choice of BORE II parameters, by examining the solution for various values of v_d and C_i . Note that care must be taken to use a consistent set of units for t , v_d , and r_w in Equations (1) and (2). For example, when time is in seconds, BORE II input parameters v_d in m/day and r_w in cm must be converted to m/s and m, respectively.

Figure 2 also shows the evolution of concentration at and near a horizontal flow layer when diffusion/dispersion along the wellbore is significant ($D_0 = 10^{-5} \text{ m}^2/\text{s}$). For this case, the analytical solution is not applicable, but BORE II results compare very well to numerically simulated data obtained using TOUGH2. When dispersion is significant, use of the Drost solution generally results in an underestimation of C_i and an overestimation of v_d . These errors do not arise when using BORE II, since diffusion/dispersion can be explicitly included.

3. Horizontal Flow – Real Data

As indicated in Figure 2, the addition of diffusion or dispersion modifies the depth-FEC profile arising from a thin layer of horizontal flow, by widening the base of the FEC peak. A thick layer of horizontal flow produces a distinct signature, with an FEC response that has a wide peak as well as a wide base. To model a thick layer of horizontal flow, one may use several adjacent inflow/outflow point pairs in the model. Figure 3 compares model and data profiles (G. Bauer, private communication, 2000) of C versus x for several times, using option R. Seven pairs of inflow/outflow points are used, assigned to seven adjacent cells. By multiplying the number of inflow/outflow pairs by cell thickness, one may estimate the thickness of the layer of horizontal flow, in this case 2.3 m. See Appendix 1, Section A1.5, for additional information about assigning feed points to specific cells.

For this particular data set, the earliest observations show a variable FEC profile. One possible way to address this is to specify a non-uniform initial concentration distribution in the wellbore. An alternative approach (used here) is to add a dummy entry to the data file, specifying a time prior to the first real data time, at which the FCE distribution in the wellbore is assumed to be uniform. In general, it is not possible to determine when, if ever, the FEC distribution in the wellbore is uniform, but the approach can work quite well, as shown in Figure

4, which shows C versus t at the center of the horizontal flow zone (option T). The data zero time taken from the header of the data file, where the date and time of the logging run are specified.

4. Down Flow – Real Data

Figure 5 compares model and data profiles (G. Bauer, private communication, 2000) of C versus x for several times (option R) for a case with primarily down flow. A uniform non-zero initial concentration is used (IC0FLAG < 0) to approximate the low, slightly variable initial concentration. Two shallow inflow points have variable concentrations that increase in time, which suggests that de-ionized water penetrated into the fractures when it was introduced into the wellbore to establish low-concentration initial conditions for logging. A low-concentration feed point at $x = 158.5$ m creates up flow above it, but the remainder of the wellbore section shows down flow.

5. Combination Flow – Real Data

Figure 6 compares model and data profiles (G. Bauer, private communication, 2000) of C versus x for several times (option R) for a case with combination flow. A non-uniform initial condition has been used, which is extracted from the data file using the preprocessor PREBORE (see Appendix 2). Note that there are more entries in the initial condition specification (232) than there are cells in the model (179). Thus, some cells are assigned more than one initial condition. For cells where this occurs, only the final initial condition assigned is used. See Appendix 1, Section A1.5, for additional information on specifying non-uniform conditions. Figure 7 shows the same information as Figure 6, but plotted in a different way, with the difference between data and model FEC plotted as an x - t plot (option I). The blue and orange diagonal features indicate that the largest discrepancy between model and data gradually deepens with time.

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Appendix 1: Mathematical Background and Numerical Approach

The principal equation governing wellbore FEC variation is the equation for the transport of mass (or ion concentration) in the wellbore. However, additional consideration must be given to the determination of FEC as a function of ion concentration and the temperature dependence of FEC.

A1.1 FEC as a Function of Concentration

The relationship between ion concentration and FEC is reviewed, for example, by Shedlovsky and Shedlovsky (1971), who give graphs and tables relating these two quantities. Hale and Tsang (1988) made a sample fit for the case of NaCl solution at low concentrations and obtained

$$\text{FEC} = 1,870 C - 40 C^2, \quad (\text{A.1})$$

where C is ion concentration in kg/m^3 ($\approx \text{g/L}$) and FEC is in $\mu\text{S/cm}$ at 20°C . The expression is accurate for a range of C up to $\approx 6 \text{ kg/m}^3$ and FEC up to $11,000 \mu\text{S/cm}$. The quadratic term can be dropped if one is interested only in values of C up to $\approx 4 \text{ kg/m}^3$ and FEC up to $7,000 \mu\text{S/cm}$, in which case the error will be less than 10%.

Fracture fluids typically contain a variety of ions, the most common being Na^+ , Ca^{2+} , Mg^{2+} , Cl^- , SO_4^{2-} , and HCO_3^- . If a hydrochemical analysis has been completed, various methods are available for computing an equivalent NaCl concentration for other ions. Schlumberger (1984) presents charts of multiplicative factors that convert various solutes to equivalent NaCl concentrations with respect to their effect on electric conductivity.

A1.2 Temperature Dependence of FEC

BORE II calculations are made assuming a uniform temperature throughout the wellbore. Actual wellbore temperatures generally vary with depth, so temperature corrections must be applied to field FEC data to permit direct comparison with model output.

The effect of temperature T on FEC can be estimated using the following equation (Schlumberger, 1984)

$$\text{FEC}(20^\circ \text{C}) = \frac{\text{FEC}(T)}{1 + S(T - 20^\circ \text{C})}, \quad (\text{A.2})$$

where $S = 0.024$.

Generally, temperature increases with depth below the land surface. If full temperature logs are available, these data can be used to correct the corresponding FEC values. However, if no complete logs are available, a simplifying assumption may be made that the temperature variation in the wellbore is linear and can be modeled by:

$$T = Ax + B, \quad (\text{A.3})$$

where A and B are parameters determined by fitting any available temperature versus depth data. If the fit is unsatisfactory, other relationships with higher order terms must be used.

A1.3 Governing Equation

The differential equation for mass or solute transport in a wellbore is:

$$\frac{\partial}{\partial x} \left(D_0 \frac{\partial C}{\partial x} \right) - \frac{\partial}{\partial x} (Cv) + S = \frac{\partial C}{\partial t}, \quad (\text{A.4})$$

where x is depth, t is time, and C is ion concentration. The first term is the diffusion term, with D_0 the diffusion/dispersion coefficient in m^2/s , the second term is the advective term, with v the fluid velocity in m/s , and S is the source term in $\text{kg}/\text{m}^3\text{s}$. This one-dimensional partial differential equation is solved numerically using the finite difference method, with upstream weighting used in the advective term. The following initial and boundary conditions are specified:

$$C(x, 0) = C_0(x), \quad (\text{A.5})$$

$$C(x_{\min}, t) = C_0(x_{\min}) \text{ for flow into the wellbore from above,}$$

$$C(x_{\max}, t) = C_0(x_{\max}) \text{ for flow into the wellbore from below,}$$

$$D_0 = 0 \text{ for } x < x_{\min} \text{ and } x > x_{\max}.$$

The first condition allows for the specification of initial ion concentrations in the wellbore. The second and third conditions allow for advective flow of ions into the wellbore interval from above and below. The final condition indicates that diffusion and dispersion do not take place across the boundaries of the wellbore interval. In general, advection will be the dominant

process at the boundaries. If diffusion or dispersion is dominant for a particular problem, the boundaries should be extended in order to prevent improper trapping of electrolyte.

A1.4 Discretization in Time

Time stepping is explicit, with the time step Δt determined by stability constraints for advection

$$\Delta t \leq \frac{\pi d_w^2 \Delta x}{8 q_{\max}}, \quad (\text{A.6})$$

and diffusion

$$\Delta t \leq \frac{\Delta x^2}{4 D_0}, \quad (\text{A.7})$$

where q_{\max} (m^3/s) is the maximum fluid flow rate anywhere in the wellbore. BORE II starts its calculation at $t = 0$. The first time in the data file is also identified with $t = 0$. If it is apparent that model and data times are not synchronized, then one may insert an additional line into the data file after the header lines, with an earlier time than the first real data time, in order to reset the data zero time. On the inserted line, FEC, x , and other data entries may be left blank or copied from the first real data line.

A1.5 Discretization in Space

The wellbore interval between x_{\min} and x_{\max} is uniformly divided into N cells and it is assumed that the wellbore has uniform diameter, d_w . Cell height Δx is determined as the larger of $(x_{\max} - x_{\min})/180$ and d_w . Position values indicate depth in the wellbore and thus x is zero at the surface and increases downward. The cell index increases upward, with cells 1 and N located at the bottom and top, respectively, of the wellbore interval. In general, the i th node (the center of the i th cell) is located at

$$x_i = x_{\max} - (i-1/2)\Delta x, \quad (\text{A.8})$$

with the i th cell extending from $x_{\max} - (i-1)\Delta x$ to $x_{\max} - i\Delta x$.

BORE II assigns feed points and initial concentrations to cell i if the location of the feed point or $C_0(x)$ value lies within the boundaries of the i th cell. If multiple feed points are assigned to the same cell, they will all be accounted for, but if multiple initial conditions are assigned to the same cell, only the final one assigned will be used. By definition, the lower boundary of cell

1 is at x_{\max} , but due to round-off errors, the upper boundary of cell N may not be at x_{\min} . Hence, it is often useful to know the x coordinates of each node. These are displayed in the input file written by BORE II (option V) when IC0FLAG > 0. Thus, if the user sets IC0FLAG = 1, inputs one $(x, C_0(x))$ pair, and uses option V, then a new input file will be created with IC0FLAG = N and a complete list of the x coordinates for all nodes, with $C_0 = 0$ for all cells except the one identified in the original input file. Alternatively, if the initial conditions are taken from the data file with PREBORE (or taken from any source that is independent of the nodal coordinates), then using option V will create an input file that shows the actual initial conditions assigned to each cell.

The list of nodal x coordinates may be useful when modeling a thick fracture zone or aquifer, in order to place one feed point in each cell over a given depth range. Similarly, when using IC0FLAG > 0 to specify non-uniform initial concentrations, one must assign a C_0 value to each cell in the interval of interest in order to obtain a continuous C profile, because no interpolation is done between scattered initial concentrations. Finally, knowing the coordinate of the top cell in the model is useful for assigning the initial concentration that serves as the boundary condition for inflow into the wellbore interval from above. For inflow from below, either $x = x_1$ or $x = x_{\max}$ may be used.

A1.6 Calculation of Flow Rates

Feed point flow rates may be constant in time, in which case a steady-state flow field is assumed in the wellbore, or variable, with feed point flow rates determined by linear interpolation between tabulated values. Although feed point flow rate may vary, true transient wellbore flow including fluid compressibility effects is not considered. Rather, the wellbore fluid flow field is assumed to change instantly from one steady-state flow field to another. In other words, the flow rate out of cell i is always the sum of the flow rates from all feed point locations within the boundaries of cell i plus the flow rate out of cell $i-1$.

Appendix 2: The Preprocessor PREBORE

PREBORE is a simple Fortran program that does preprocessing for BORE II. It runs under either Windows or DOS. PREBORE converts the old BORE data file format into the new BORE II data file format. Depth is converted from feet to meters, and other data columns are realigned. PREBORE can also create a file with (x, C_0) pairs to be added to the BORE II input file as initial conditions (this option requires that x values steadily increase or steadily decrease in each profile).

If data file conversion is being done, the user is prompted to enter the old and new data file names.

If a file with initial conditions is being created, the user is prompted for the following information: the name of the BORE II data file; a name for the initial condition file; which profile in the data file to use; the direction of logging (downward assumes x values increase in the data file, upward assumes they decrease, and both assumes the profiles alternately increase and decrease in x); and the conversion factors (γ, β, α) between FEC and C (default values 0, 1870, -40). In addition to creating an ASCII text file with (x, C_0) pairs, which may be added to the BORE II input file using a text editor or word processor, PREBORE prints out the number of pairs on the screen, which should be used for IC0FLAG. Note that IC0FLAG may be greater than the number of cells in the model (usually about 180), but that in this case not all the C_0 values will be used (see Appendix 1, Section A1.5).

Data file conversion and initial condition creation can be done in the same PREBORE run. In this case the user must specify both old and new data file names in addition to the parameters describing the creation of initial conditions.

Appendix 3: Input Files for Example Applications

A2.1 Example Application 1 – Up Flow – up_num.inp

```

TITLE: up flow with flow from below, compare to synthetic data
XMIN(m)      XMAX(m)      DIAM(cm)      !DX(m) = MAX(|XMIN - XMAX|/180, DIAM/100)
.0000        180.0        14.00        ! 1.000
QW(L/min)     HALPHA      !QW=flow from below; HALPHA=hor. flow constriction
.7500        2.500
#FEED_PTS     VARIABLE_FLOWRATE_IDENTIFIER
3            999
DEPTH(m)      Q(L/min)     C(g/L)      T0(hr)      Q/V_FLAG      !Vd(m/day)
160.5         .7500        100.0        .0000        0
130.5         .7500        100.0        .0000        0
50.50         .7500        100.0        .0000        0
TMAX(hr)      FECMAX      DIFFUSION_COEF.(m2/s)
24.00         100.0        .7500E-09
RGAMMA        RBETA       RALPHA      !FEC = RGAMMA + C*RBETA + C*C*RALPHA
.0000         1.000        .1000E-07
IC0FLAG       !If 0, C0=0; If <0, read one C0; If >0, read IC0FLAG (X,C0) pairs
0
DATA_FILE     !'NONE' if there is no data file
up_num.dbt

```

A2.2 Example Application 2 – Horizontal Flow Analytical Solution – hor_an.inp

```

TITLE: Horizontal Flow - Compare to Analytical Solution
XMIN(m)      XMAX(m)      DIAM(cm)
0.000        50.000        7.600
QW(L/min)     HALPHA
0.           2.850000
#FEED_PTS     VARIABLE_FLOWRATE_IDENTIFIER
2            999
DEPTH(m)      Vd(m/d)     C(g/L)      T0(hr)      Q/V_FLAG
25.0000       1.         1000.        .0000        1
25.0000       -1.        1000.        .0000        1
TMAX(hr)      FECMAX      DIFFUSION_COEF.(m2/s)
3.0000        1000.        1.e-10
RGAMMA        RBETA       RALPHA
0.000000      1.000000    1.e-08
IC0FLAG
0
DATA_FILE
hor_an.dbt

```

The input file for the case with significant dispersion is identical, except that the diffusion coefficient is increased from $10^{-10} \text{ m}^2/\text{s}$ to $10^{-5} \text{ m}^2/\text{s}$.

A2.3 Example Application 3 – Horizontal Flow - hor_real.inp

```

TITLE: Horizontal Flow Example
XMIN(m)      XMAX(m)      DIAM(cm)      !DX(m) = MAX(|XMIN - XMAX|/180, DIAM/100)
.0000        60.00        7.600        ! .3333
QW(L/min)     HALPHA      !QW=flow from below; HALPHA=hor. flow constriction
.0000        2.500
#FEED_PTS     VARIABLE_FLOWRATE_IDENTIFIER
14           999
DEPTH(m)      Q(L/min)     C(g/L)        T0(hr)        Q/V_FLAG      !Vd(m/d)
26.73         .5295E-02    730.0        .0000         0             ! .1204
26.73         -.5295E-02   .0000        .0000         0             !-.1204
26.39         .5295E-02    730.0        .0000         0             ! .1204
26.39         -.5295E-02   .0000        .0000         0             !-.1204
26.06         .5295E-02    730.0        .0000         0             ! .1204
26.06         -.5295E-02   .0000        .0000         0             !-.1204
25.73         .5295E-02    730.0        .0000         0             ! .1204
25.73         -.5295E-02   .0000        .0000         0             !-.1204
25.39         .5295E-02    730.0        .0000         0             ! .1204
25.39         -.5295E-02   .0000        .0000         0             !-.1204
25.06         .5295E-02    730.0        .0000         0             ! .1204
25.06         -.5295E-02   .0000        .0000         0             !-.1204
24.73         .5295E-02    730.0        .0000         0             ! .1204
24.73         -.5295E-02   .0000        .0000         0             !-.1204
TMAX(hr)      FECMAX      DIFFUSION_COEF.(m2/s)
4.000         400.0        .7500E-04
RGAMMA        RBETA       RALPHA      !FEC = RGAMMA + C*RBETA + C*C*RALPHA
.0000         1.000        .1000E-07
IC0FLAG       !If 0, C0=0; If <0, read one C0; If >0, read IC0FLAG (X,C0) pairs
0
DATA_FILE     !'NONE' if there is no data file
hor_real.dbt

```

A2.4 Example Application 4 – Down Flow – down_c.inp

```

TITLE: downflow, variable source conc., uniform non-zero initial conc.
XMIN(m)      XMAX(m)      DIAM(cm)      !DX(m) = MAX(|XMIN - XMAX|/180, DIAM/100)
140.0         240.0         7.600         ! .5556
QW(L/min)     HALPHA       !QW=flow from below; HALPHA=hor. flow constriction
.0000         2.850
#FEED_PTS     VARIABLE_FLOWRATE_IDENTIFIER
12            999
DEPTH(m)      Q(L/min)     C(g/L)         T0(hr)         Q/V_FLAG      !Vd(m/day)
239.0         -.7000       .0000         .4000         0
212.0         -1.000       .0000         .4000         0
187.0         .7500        1800.         .4000         0
183.0         .1900        1900.         .4000         0
181.0         .1200        1900.         .4000         0
178.0         .5000E-01    1900.         .4000         0
176.0         .4000E-01    1900.         .4000         0
174.0         .3000E-01    1900.         .4000         0
171.0         .1000E-01    1900.         .4000         0
164.4         99905.       1900.         .4000         0
      T(hr)      Q(L/min)     C(g/L)         !#entries is two digits after 999
      .0000      .4400        80.00
      .4000      .4400        100.0
      1.200      .4400        1100.
      1.900      .4400        1650.
      4.500      .4400        1950.
162.0         99904.       1800.         .0000         0
      T(hr)      Q(L/min)     C(g/L)         !#entries is two digits after 999
      .0000      .6000E-01    80.00
      .4000      .6000E-01    200.0
      1.900      .6000E-01    1650.
      4.500      .6000E-01    1950.
158.5         .1000        80.00         .0000         0
TMAX(hr)      FECMAX       DIFFUSION_COEF.(m2/s)
4.400         1700.         .1000E-02
RGAMMA        RBETA        RALPHA         !FEC = RGAMMA + C*RBETA + C*C*RALPHA
.0000         1.000        .1000E-07
IC0FLAG       !If 0, C0=0; If <0, read one C0; If >0, read IC0FLAG (X,C0) pairs
-1
C0 (g/L)       !Uniform, non-zero C0
80.00
DATA_FILE      !'NONE' if there is no data file
down_c.dbt

```

A2.5 Example Application 5 – Combination Flow – comb_ic.inp

```

TITLE: Combination flow example, non-uniform initial concentration
XMIN(m)      XMAX(m)      DIAM(cm)      !DX(m) = MAX(|XMIN - XMAX|/180, DIAM/100)
.00000      50.000      7.6000      ! .2778
QW(L/min)     HALPHA      !QW=flow from below; HALPHA=hor. flow constriction
.00000      2.8500
#FEED_PTS     VARIABLE_FLOWRATE_IDENTIFIER
12           999
DEPTH(m)      Q(L/min)      C(g/L)      T0(hr)      Q/V_FLAG      !Vd(m/day)
45.000      -.13000      .00000      .00000      0
33.300      .11000      800.00      .15000      0
33.300      -.31000      .00000      .00000      0
27.500      -1.0500      .00000      .00000      0
25.700      .30000      810.00      .15000      0
25.400      .30000      810.00      .15000      0
25.140      .30000      810.00      .15000      0
24.900      .30000      810.00      .15000      0
23.500      .12000      800.00      .15000      0
21.500      .40000E-01      800.00      .15000      0
14.000      .15000E-01      750.00      .15000      0
12.200      .10000E-01      750.00      .15000      0
TMAX(hr)      FECMAX      DIFFUSION_COEF.(m2/s)
1.0000      1000.0      .50000E-03
RGAMMA      RBETA      RALPHA      !FEC = RGAMMA + C*RBETA + C*C*RALPHA
.00000      1.0000      .10000E-07
IC0FLAG      !If 0, C0=0; If <0, read one C0; If >0, read IC0FLAG (X,C0) pairs
232
X(m)      C0(g/L)      !#entries is IC0FLAG
1.524      2
1.615      2
1.707      3
1.829      3
1.951      3
2.073      3
2.225      3
2.377      3
2.53      3
2.713      3
2.865      3
3.018      3
3.353      589
3.536      597
3.719      588
3.871      583
4.054      584
...(208 entries not shown)...
43.282      2
43.8      2
43.983      2
44.166      1
44.318      1
44.501      1
44.684      1
DATA_FILE      !'NONE' if there is no data file
comb_ic.dbt

```

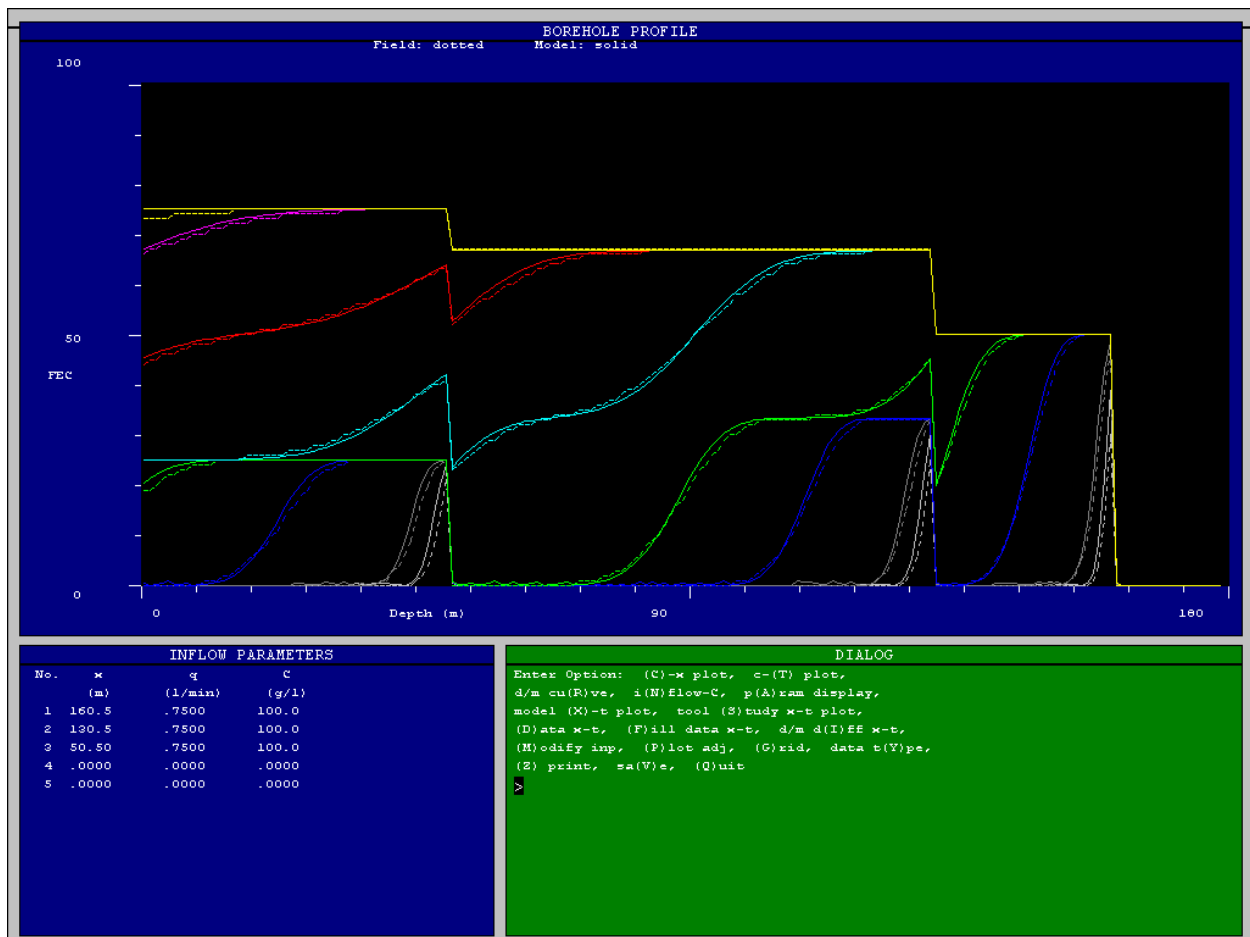


Figure 1. Concentration (=FEC) versus depth at a series of times for example application 1 - up flow. Data are numerically simulated using the TOUGH2 code. Figure is a BORE II screen-print after running option R.

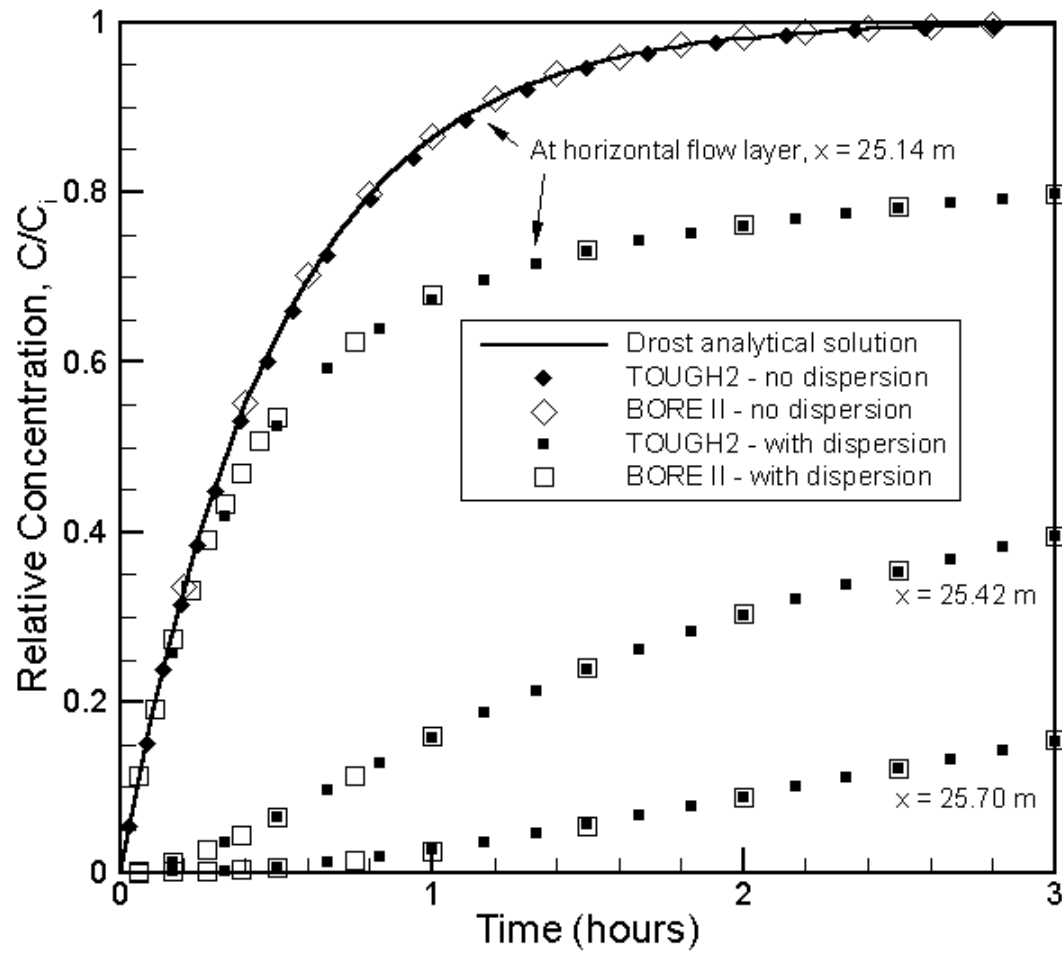


Figure 2. Relative concentration versus time for example application 2 – horizontal flow. When diffusion/dispersion is negligible, the concentration increase only occurs at the depth of the horizontal flow layer. The solid line shows the analytical solution as given by Drost et al. (1968), Equation (1).

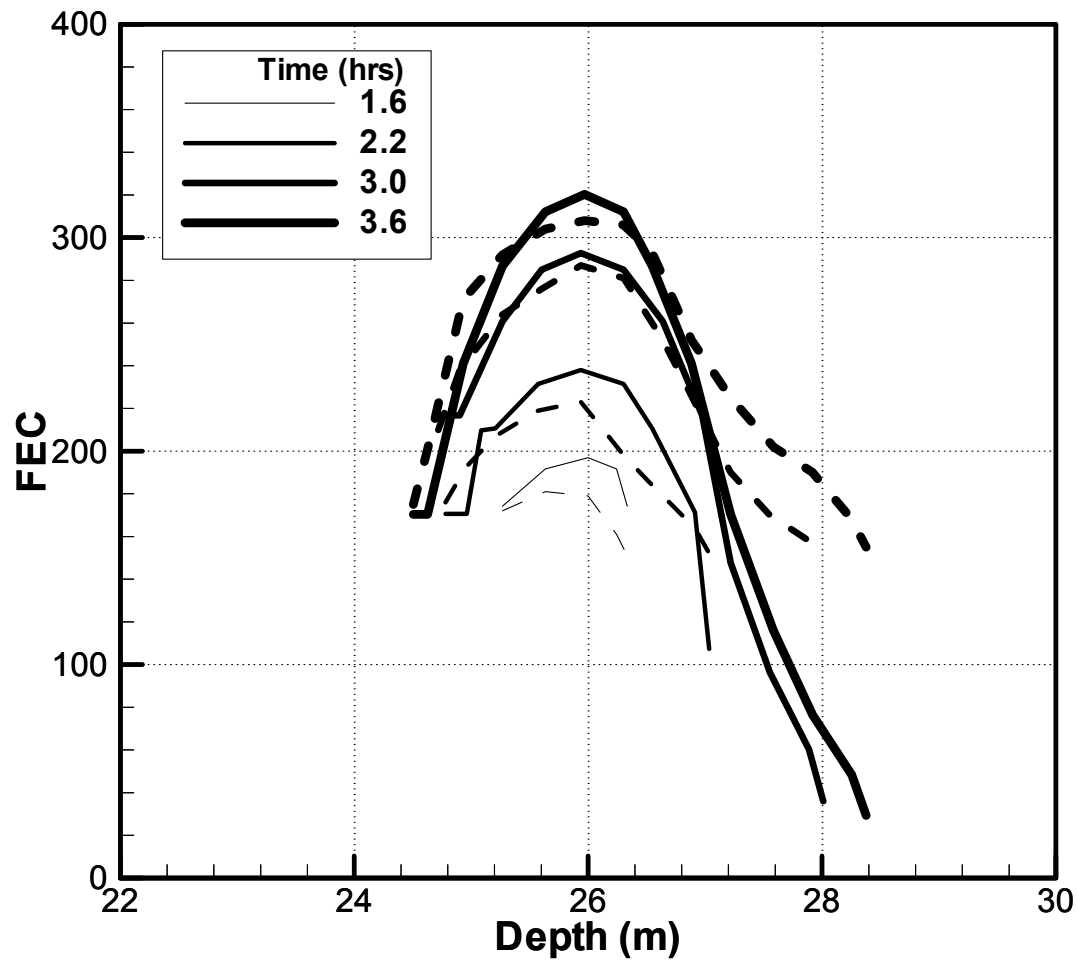


Figure 3. Concentration (= FEC) versus depth at a series of times for example application 3 – a thick layer of horizontal flow. Dashed lines represent field data, solid lines represent BORE II results. Diffusion/dispersion is significant.

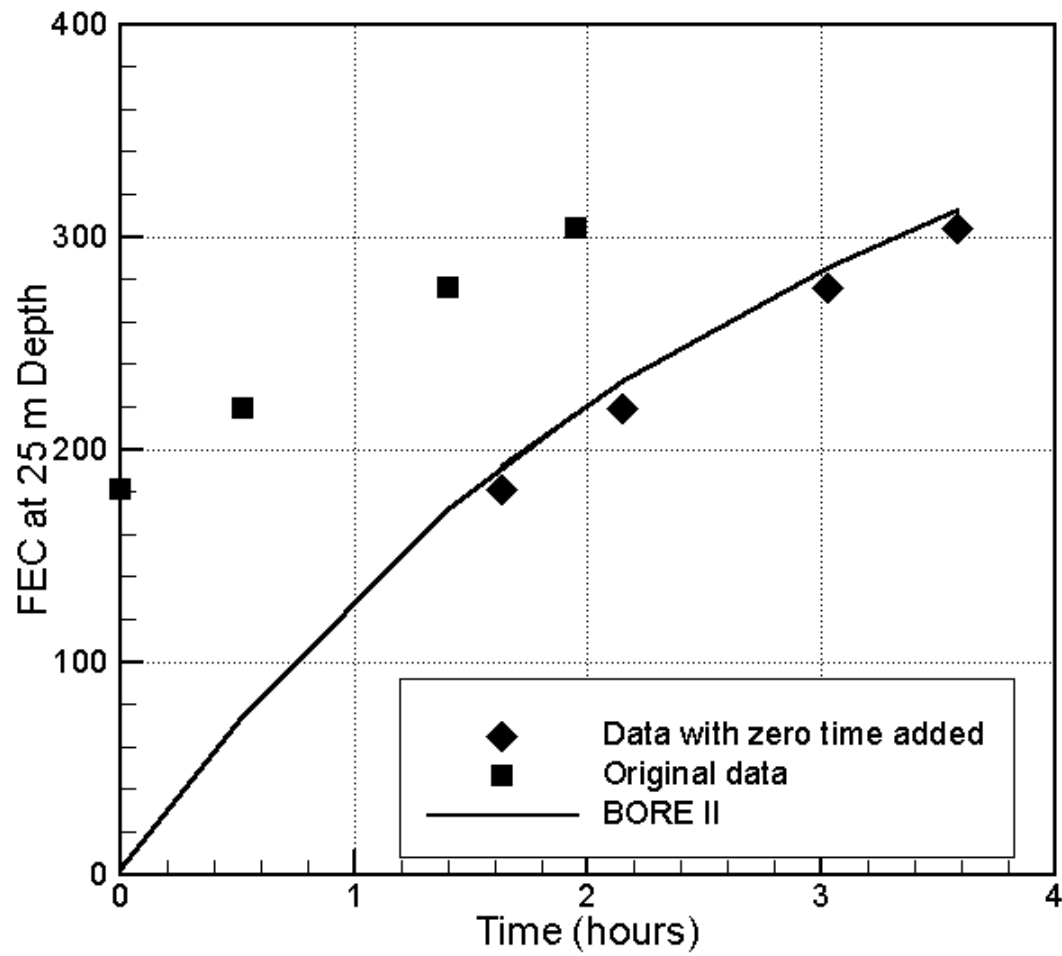


Figure 4. Concentration (= FEC) versus time at the center of the horizontal flow zone of example application 3, illustrating the addition of a data zero time.

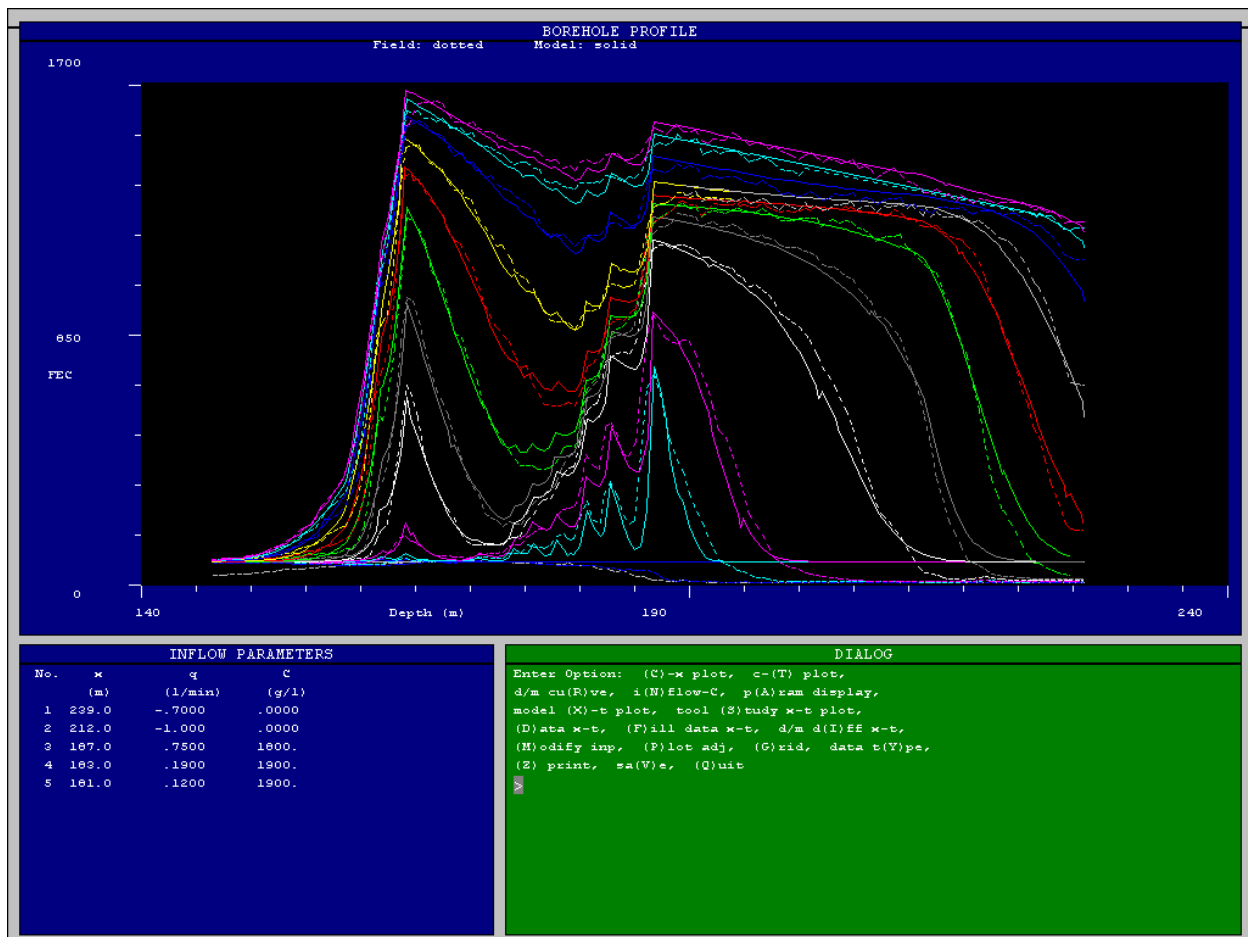


Figure 5. Concentration (= FEC) versus depth at a series of times for example application 4 – down flow. Figure is a BORE II screen-print after running option R.

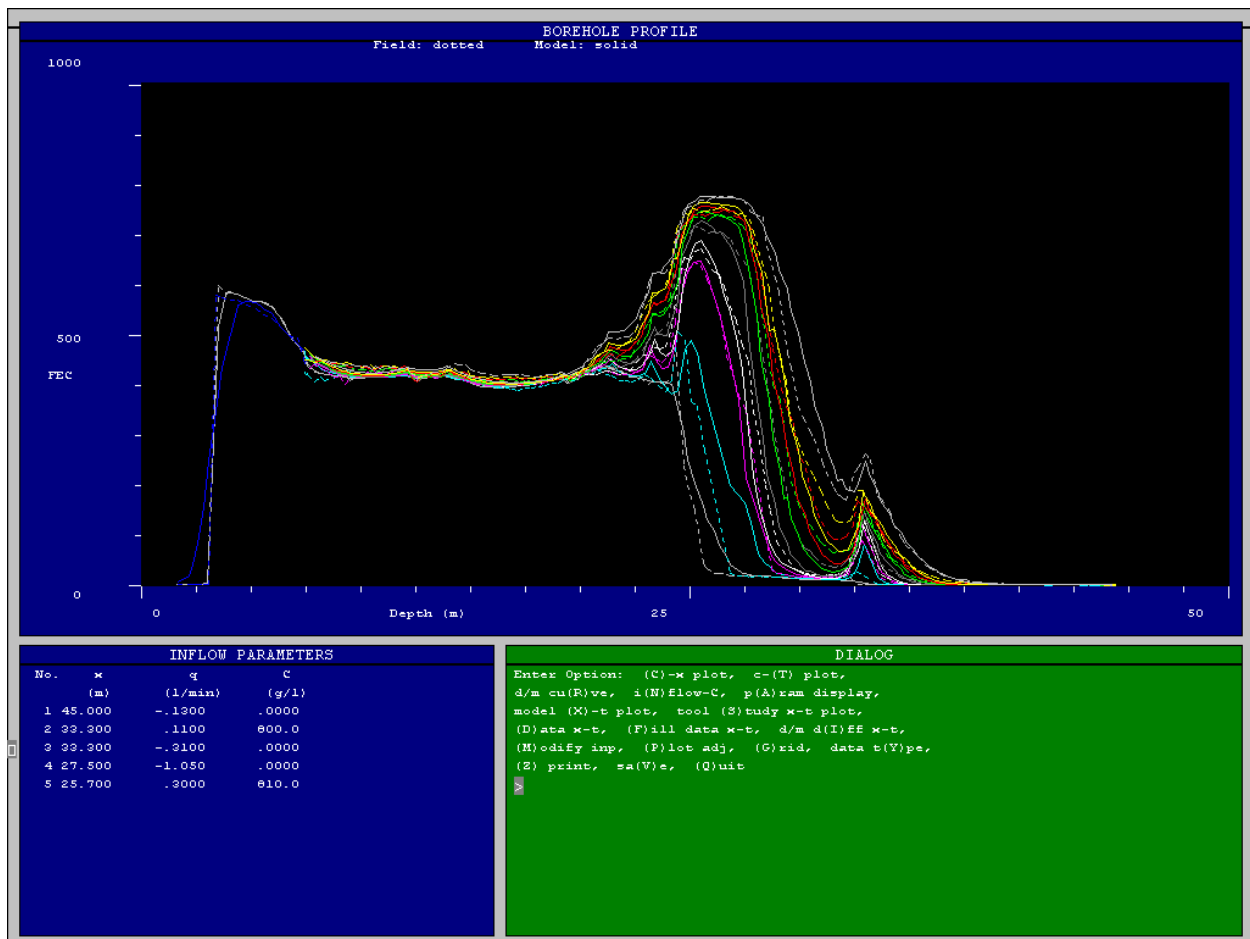


Figure 6. Concentration (= FEC) versus depth at a series of times for example application 5 – combination flow. Figure is a BORE II screen-print after option R.

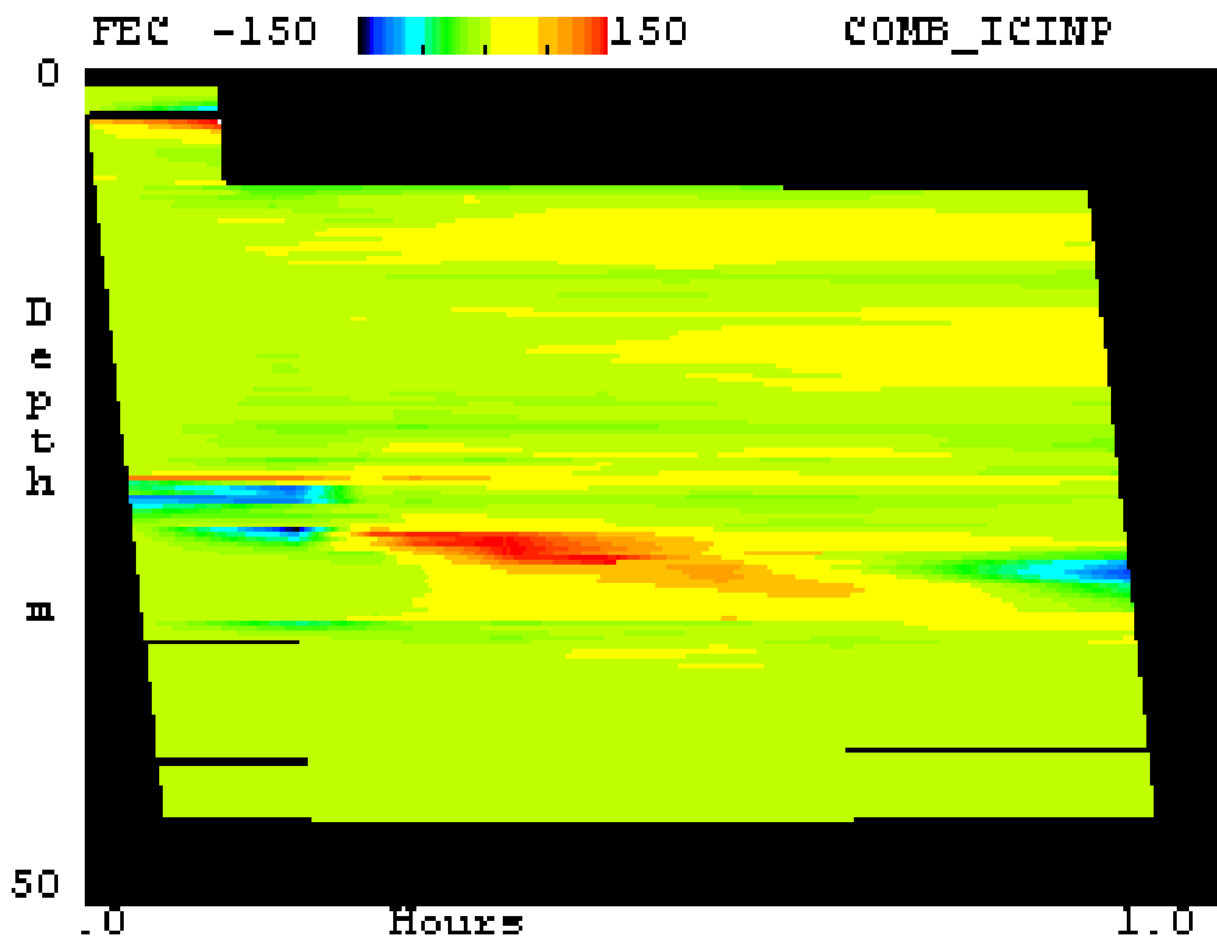


Figure 7. FEC difference between model and data as a function of depth and time (an $x-t$ plot) for example application 5 – combination flow. Figure is a BORE II screen-print after option I, mode 2.